Jet Propulsion Laboratory
California Institute of Technology

Ion Propulsion

and the Job-Creating Power of the Rocket Equation

January 17, 2018

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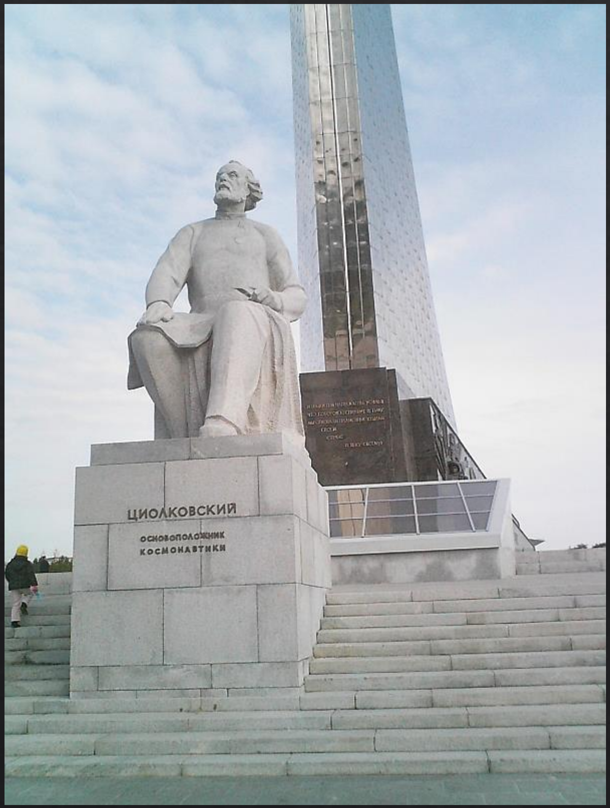
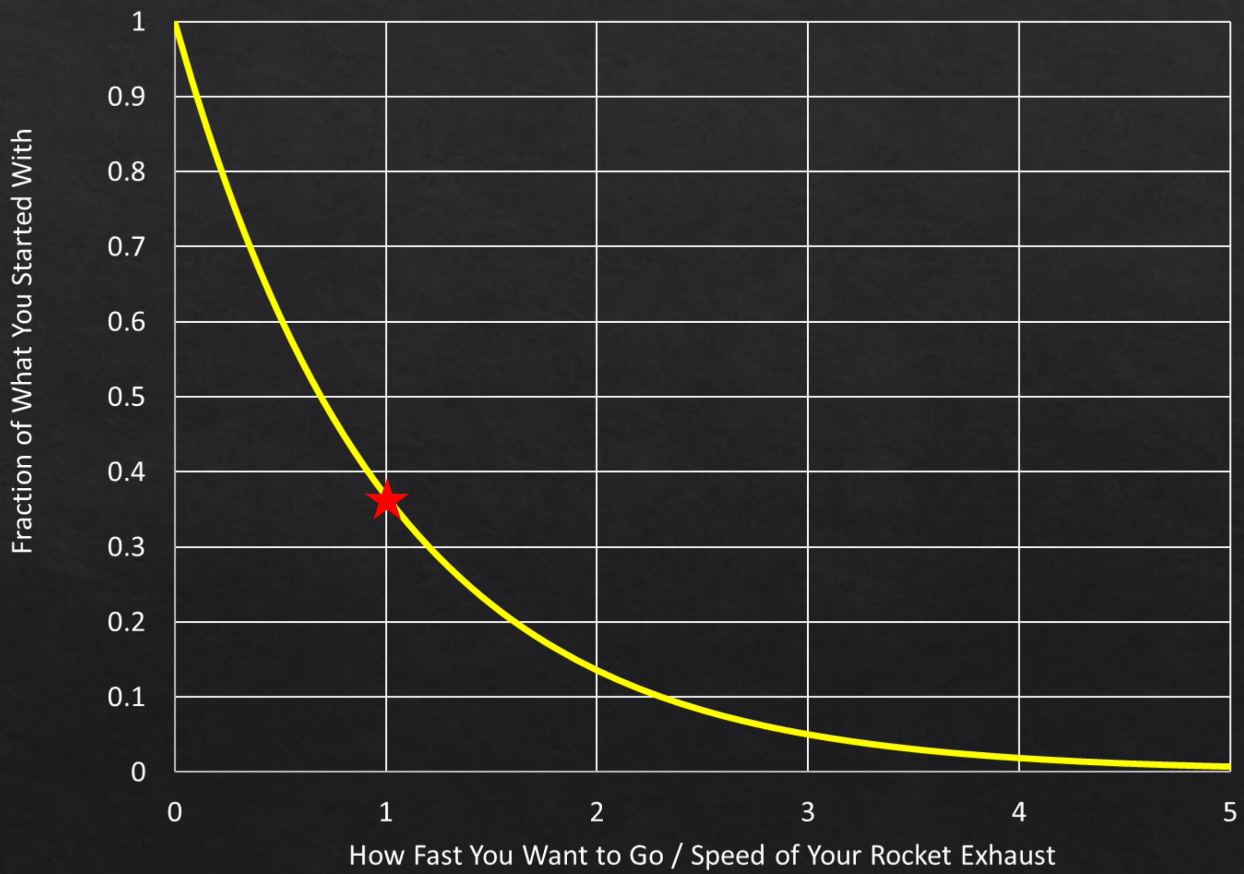
Rocket Equation

$$\frac{m_f}{m_i} = e^{-\frac{v_{s/C}}{v_{ex}}}$$

If your exhaust velocity is about the same speed you want your spacecraft to go then nearly 2/3rds of your initial mass is propellant





Specific Impulse

For a propellant mass that weighs 1 N at the Earth's surface,
How long can you sustain a thrust of 1 N?

Thrust: $T = \dot{m} v_{ex}$

Time to exhaust all the propellant: $t = \dfrac{M_p}{\dot{m}}$

$$W_p = M_p g \rightarrow M_p = \frac{W_p}{g}$$

$$t = \frac{W_p v_{ex}}{T g}$$

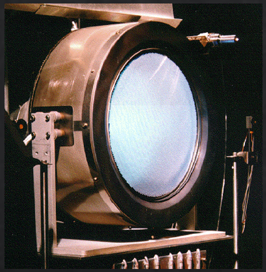
for $W_p = T = 1$, then $t = \dfrac{v_{ex}}{g} \equiv I_{sp}$

Specific Impulse

Xenon Hall
Thruster (ARRM)

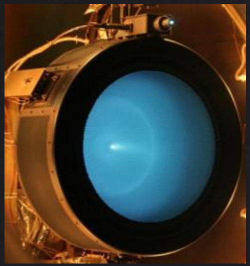
Isp = 2800 s
(28 km/s)

Xenon Ion Thruster
(Dawn)



Isp = 3100 s
(31 km/s)

Xenon Ion Thruster
(NEXT)

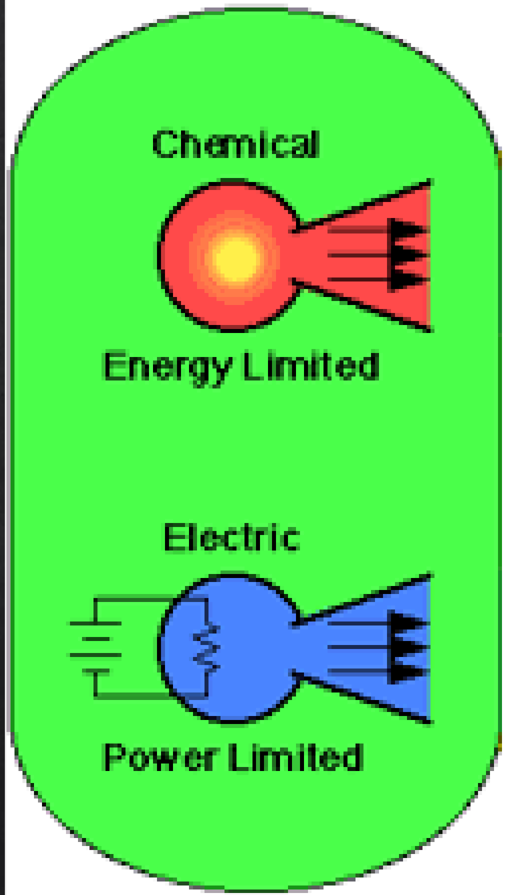


Isp = 4000 s
(40 km/s)

Chemical vs Electric Propulsion

- **Chemical propulsion systems:**
  - Carry the energy for propulsion with the propellant
  - Power is determined by the propellant mass flow rate
  - Performance is limited by the energy density of the propellants

- **Electric propulsion systems:**
  - Decouple the energy for propulsion from the propellants – allows more energy to be added to each kg of propellant
  - Power is generated on-board by a separate power system
  - Performance is limited by the power generated by the power system



$$E = \frac{1}{2} m v^2 \rightarrow v = 1.41 \sqrt{\frac{E}{m}}$$

$$\left.\begin{aligned} P &= \frac{1}{2} \dot{m} v^2 \\ T &= \dot{m} v \end{aligned}\right\} \quad v = \sqrt{\frac{2P}{\dot{m}}} \qquad \dot{m} = \frac{2P}{v^2} \qquad T = \frac{2P}{v}$$

Visionaries

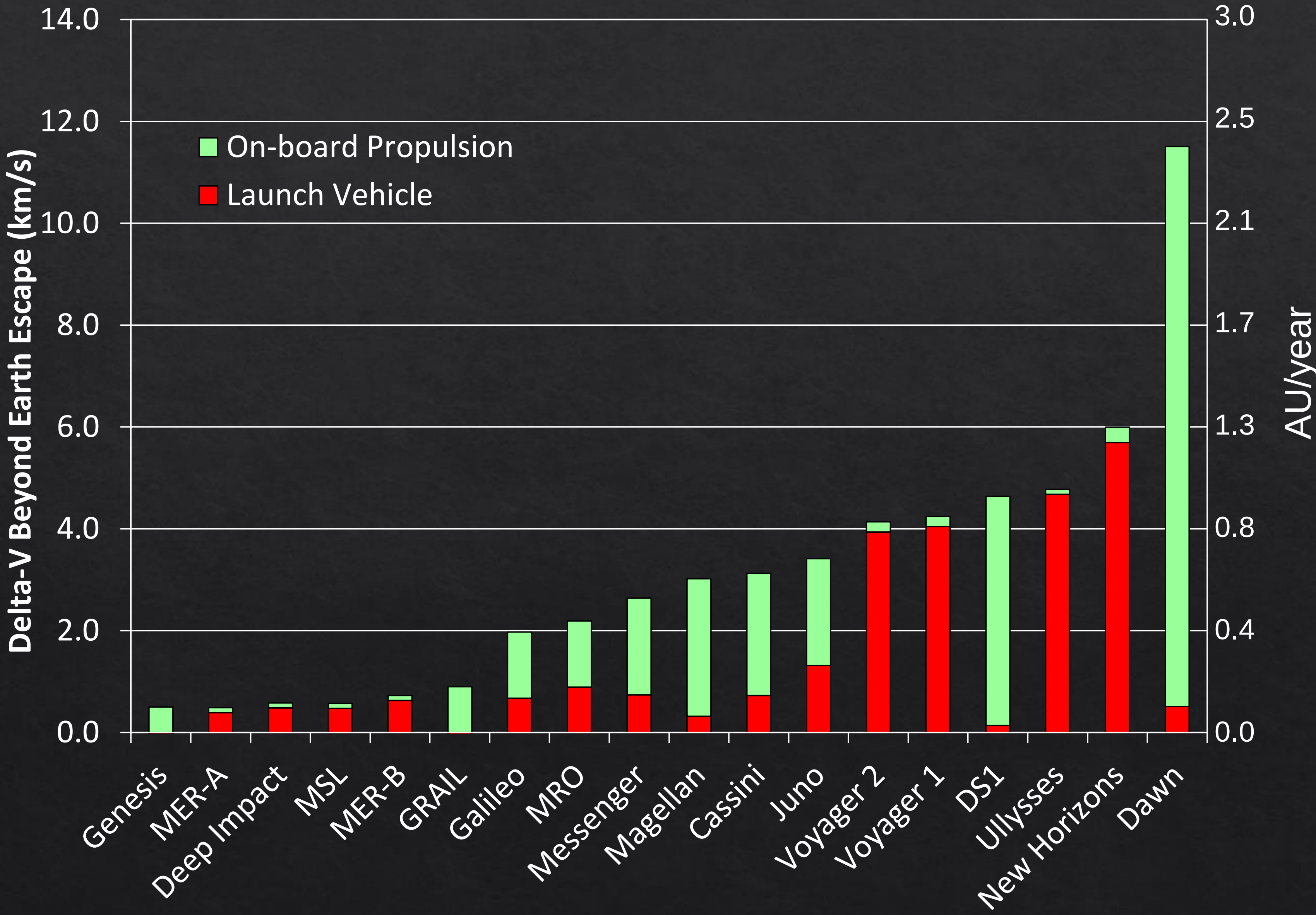
1906: Robert Goddard’s notebook discusses the idea that electrostatically repelled particles might be the answer to the problem of obtaining high exhaust velocities at bearable chamber temperatures

1929: Hermann Oberth devotes an entire chapter to electric propulsion in his classic book on rocketry and space travel

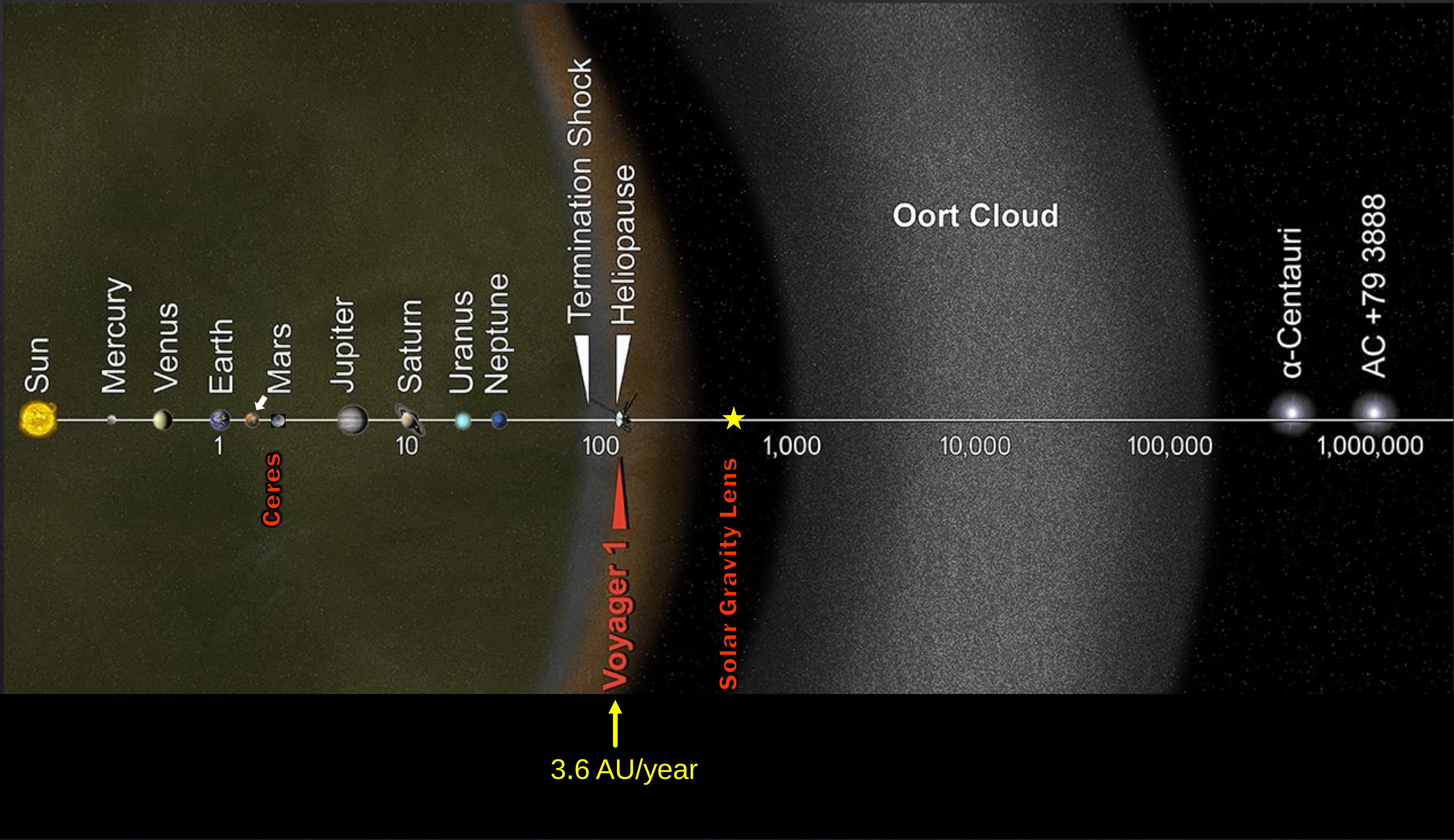
1947: Werner von Braun, “Professor Oberth has been right with so many of his early proposals; I wouldn’t be surprised if one day we flew to Mars electrically!”

1960: Ernst Stuhlinger’s, book Electric Propulsion, destined to become a classic read by every EP student.

ΔV Beyond Earth Escape



Space is BIG



Sun
Mercury
Venus
Earth
Mars
Ceres
Jupiter
Saturn
Uranus
Neptune
Termination Shock
Heliopause
Voyager 1
Solar Gravity Lens
Oort Cloud
α-Centauri
AC +79 3888
1
10
100
1,000
10,000
100,000
1,000,000
3.6 AU/year

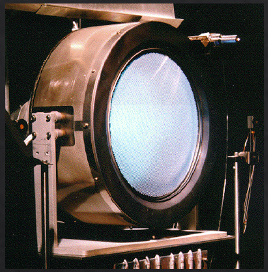
Specific Impulse

Xenon Hall Thruster (ARRM)

Isp = 2800 s

5.9 AU/year

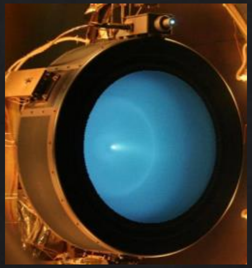
Xenon Ion Thruster (Dawn)



Isp = 3100 s

6.5 AU/year

Xenon Ion Thruster (NEXT)



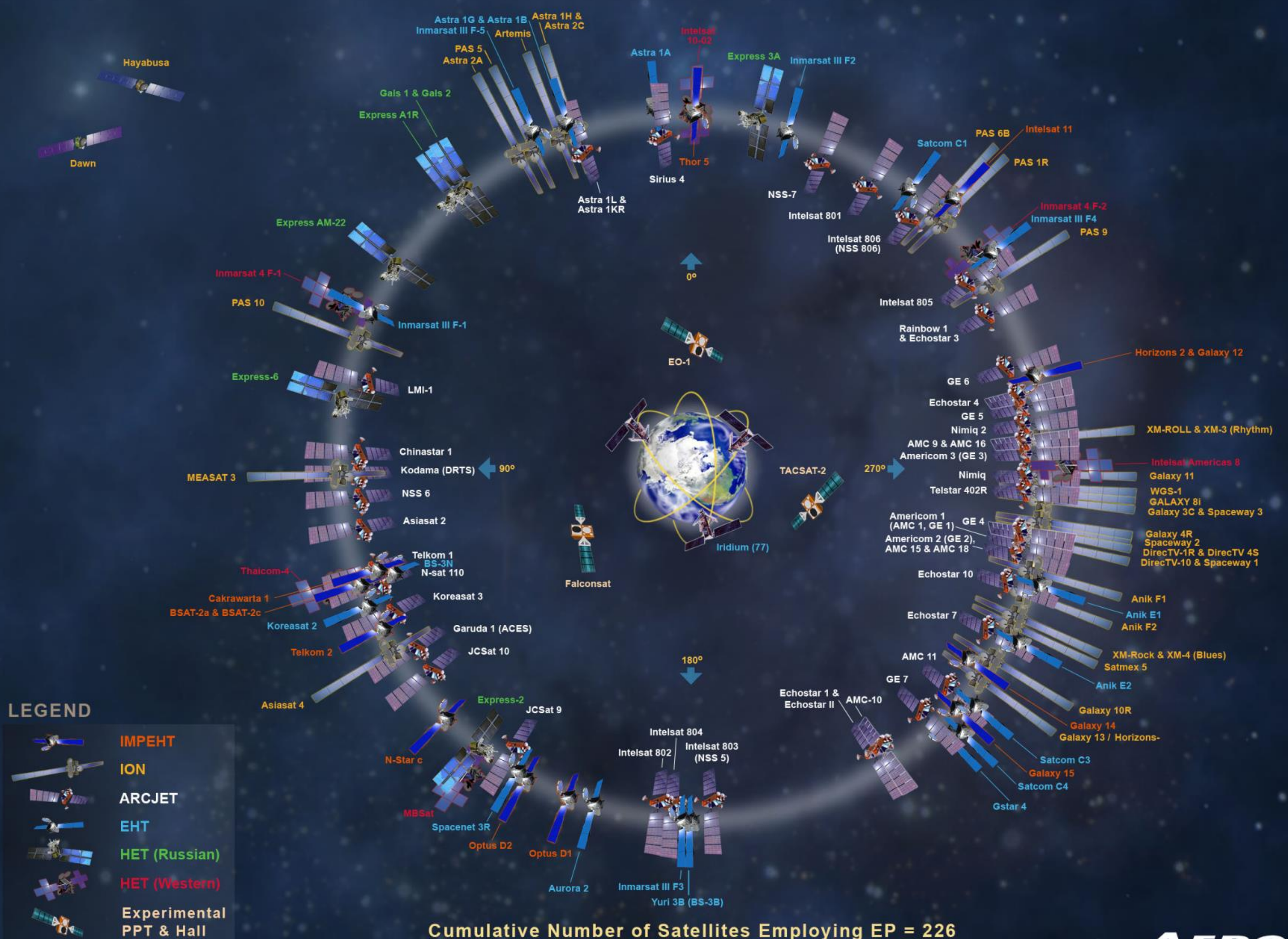
Isp = 4000 s

8.4 AU/year

Commercial Spacecraft

(0.050 m/s/year x 15 years = 0.75 km/s)

Operational Satellites with Electric Propulsion



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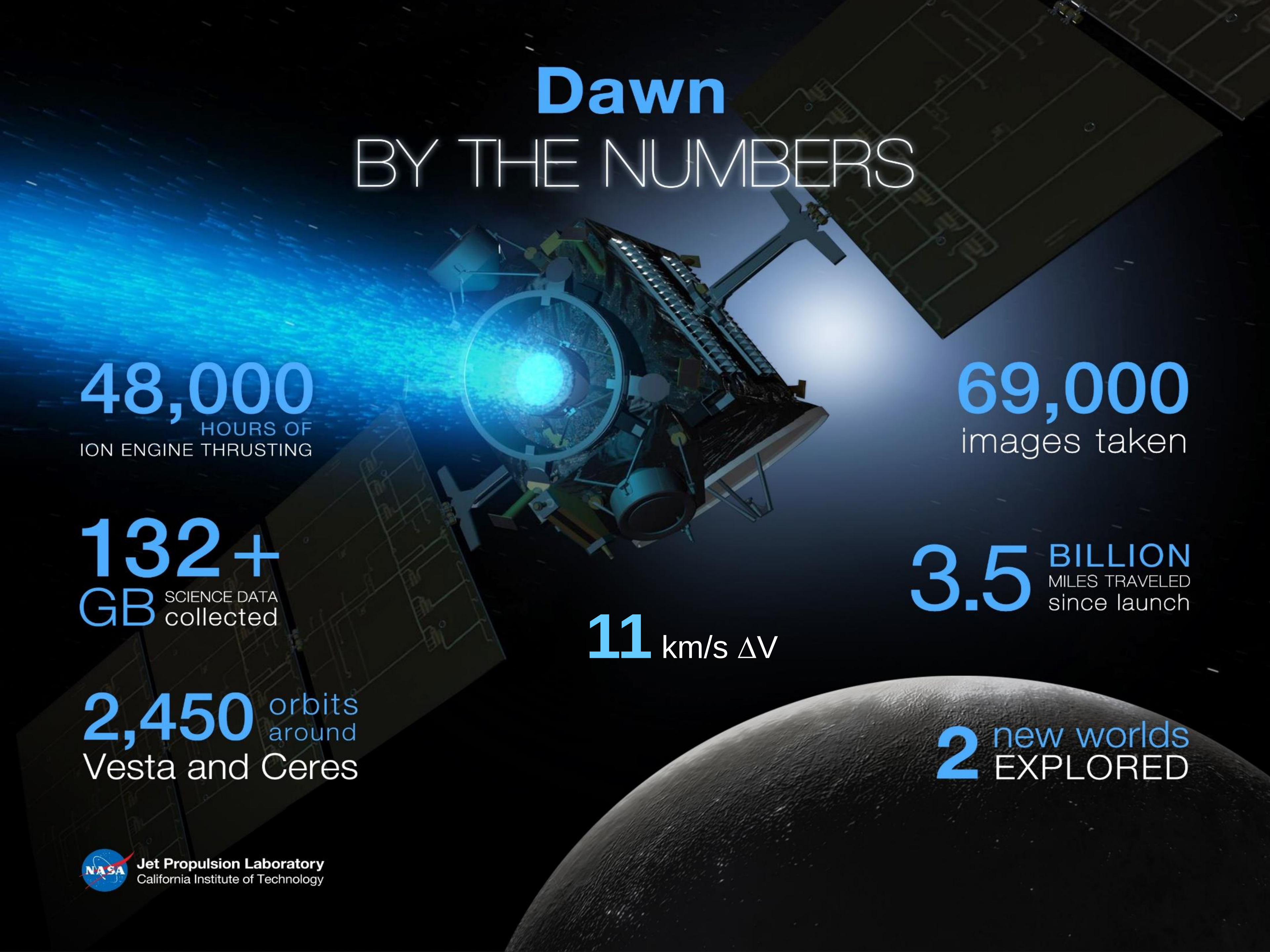
Cumulative Number of Satellites Employing EP = 226
Number of Satellites Employing Aerojet EP = 156

AEROJET

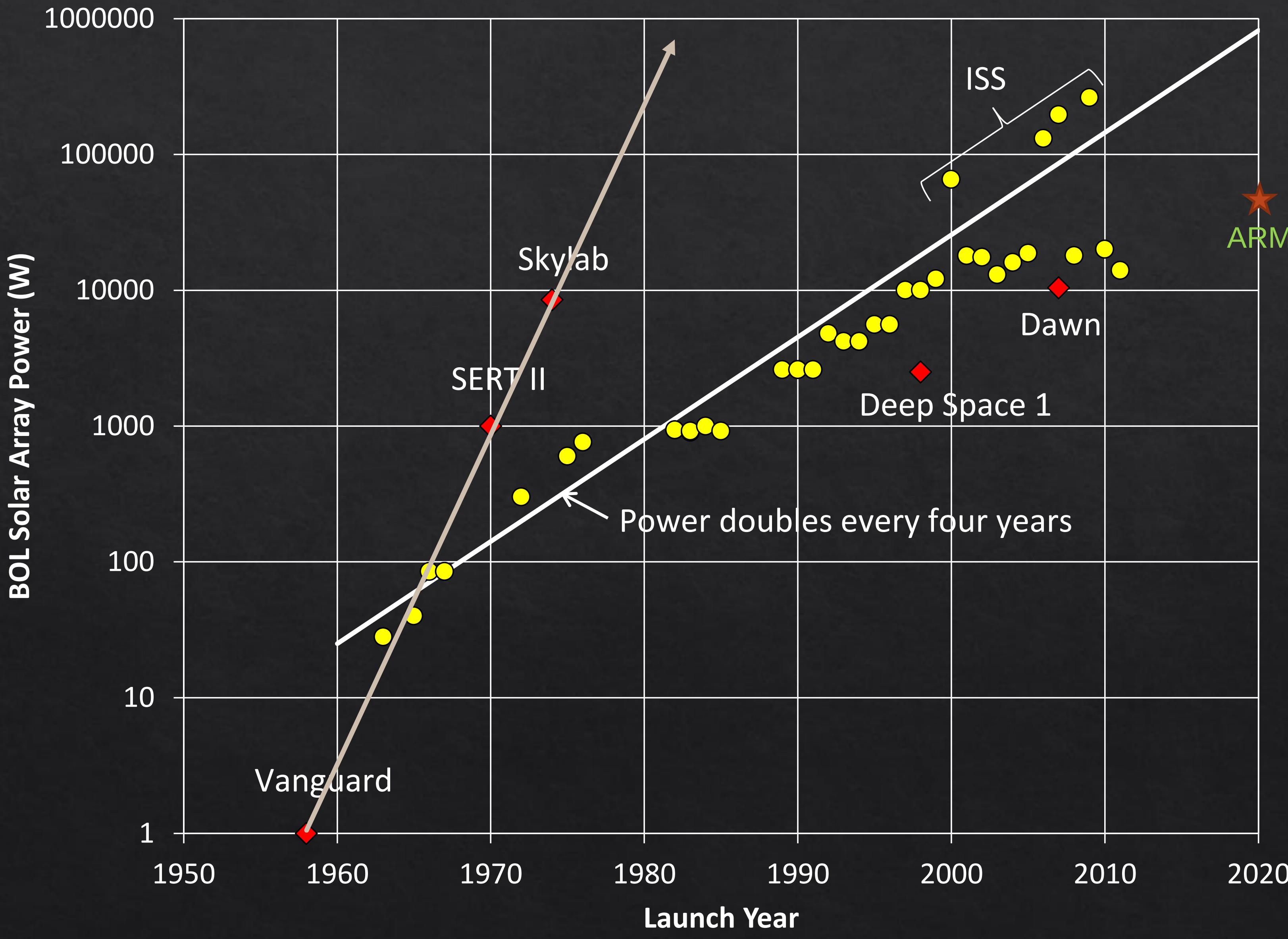
Deep Space Missions


Dawn
BY THE NUMBERS
48,000
HOURS OF
ION ENGINE THRUSTING
69,000
images taken
132+
GB SCIENCE DATA
collected
3.5 BILLION
MILES TRAVELED
since launch
11 km/s ΔV
2,450 orbits
around
Vesta and Ceres
2 new worlds
EXPLORED
NASA
Jet Propulsion Laboratory
California Institute of Technology

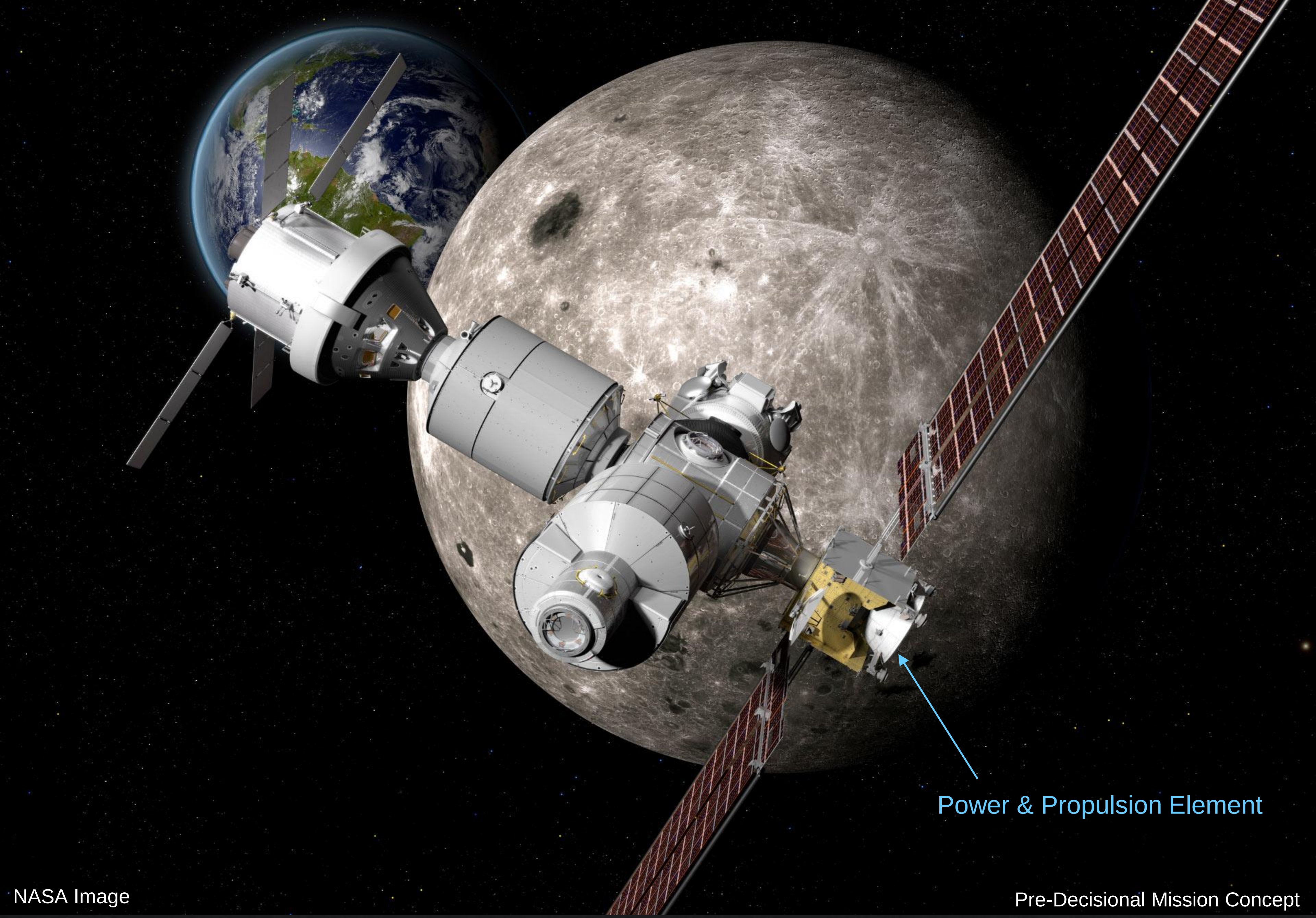
Human Exploration Beyond Low-Earth Orbit

It's All About Power

Space Solar Power History



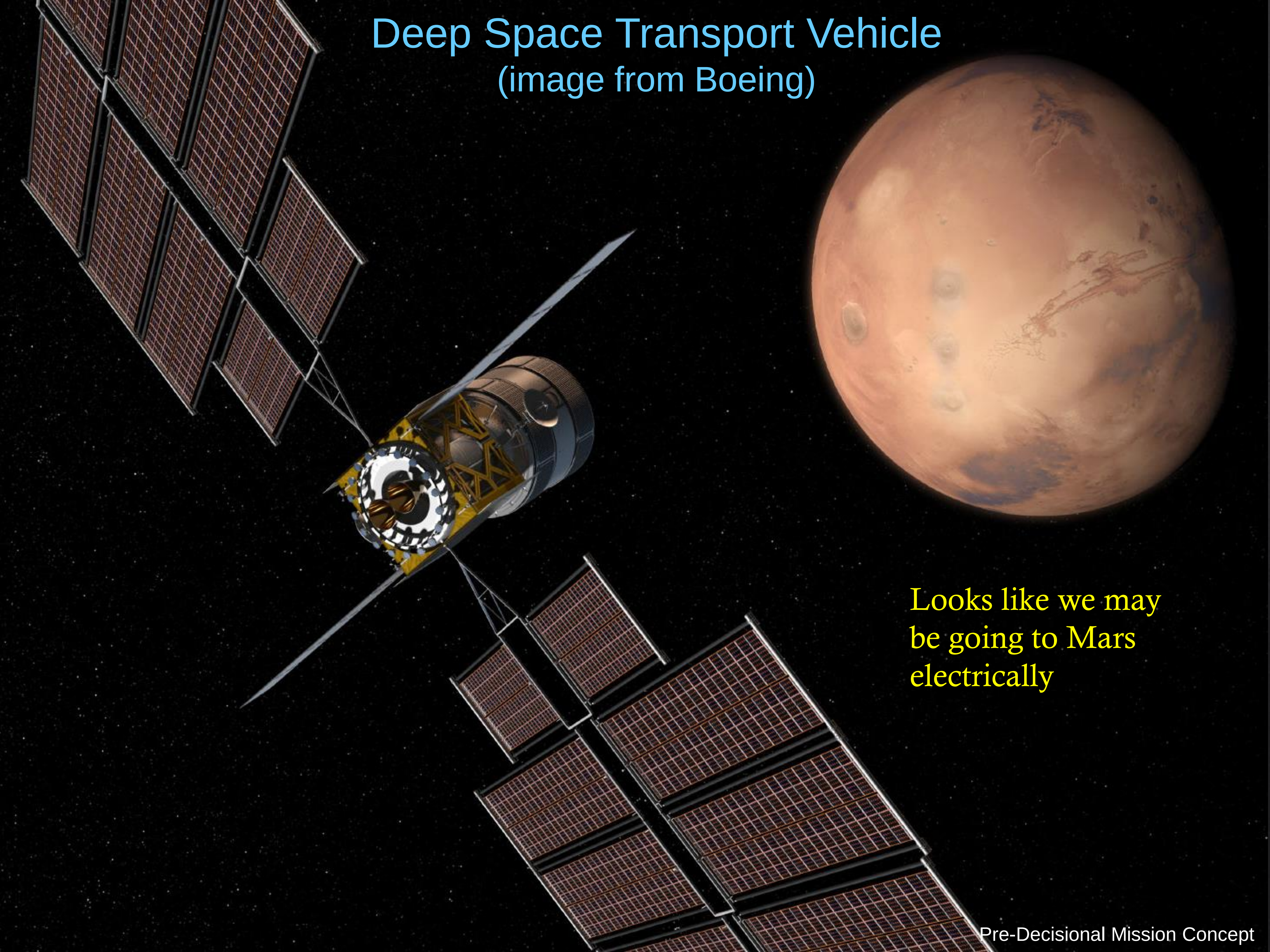
NASA's Deep Space Gateway Concept



NASA Image

Pre-Decisional Mission Concept

Deep Space Transport Vehicle
(image from Boeing)



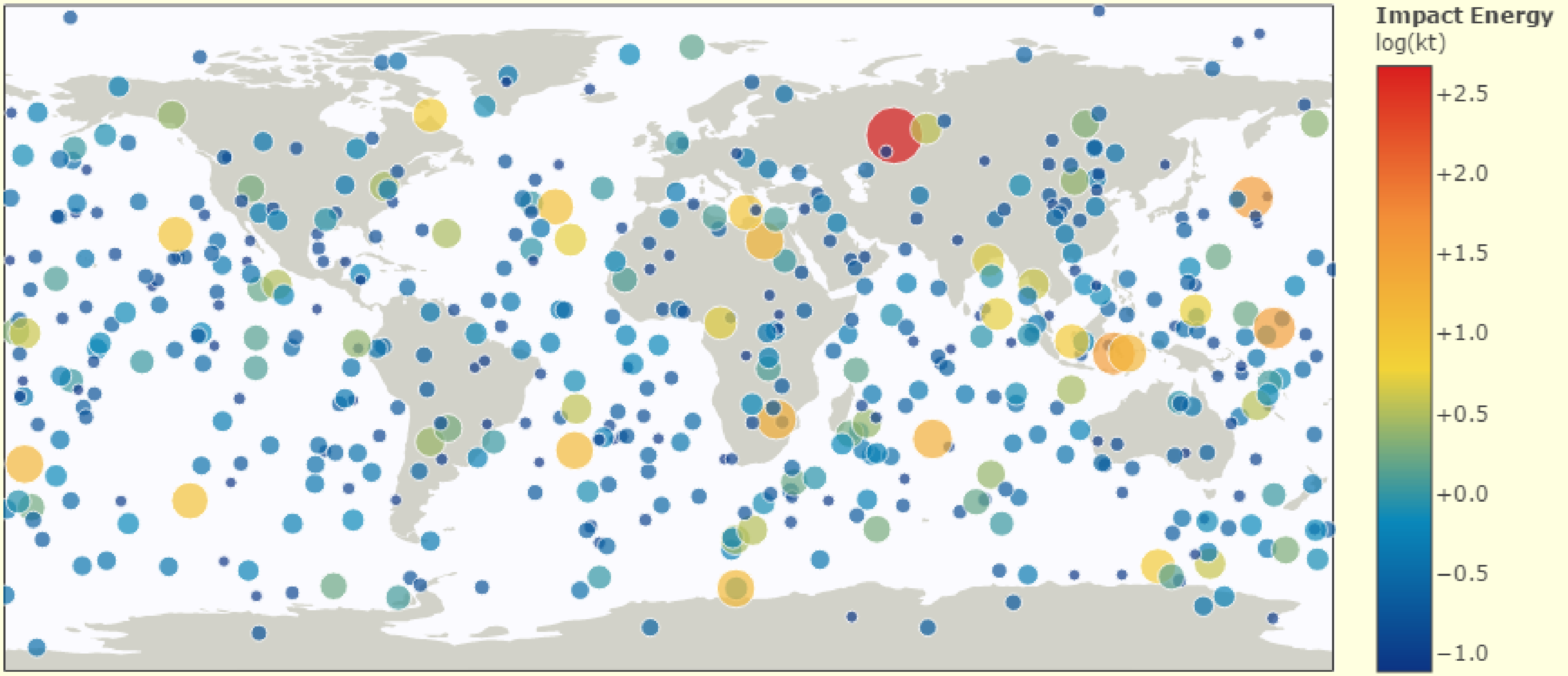
Looks like we may be going to Mars electrically

Pre-Decisional Mission Concept

Planetary Defense

Fireballs Reported by US Government Sensors

(1988-Apr-15 to 2017-Mar-11)



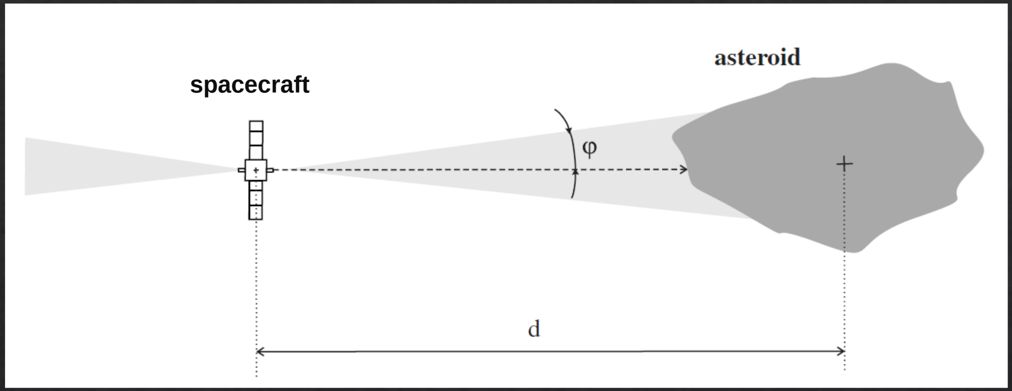
https://cneos.jpl.nasa.gov/fireballs/

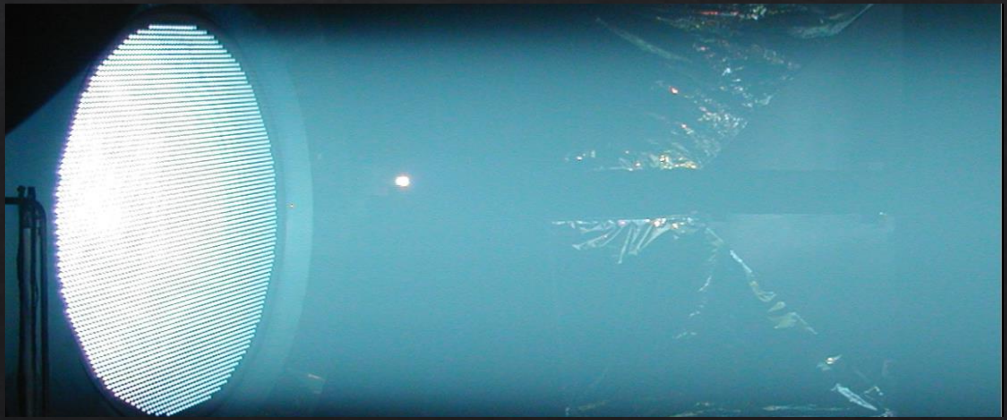
Alan B. Chamberlin (JPL/Caltech)

Ion Beam Deflection

Key Features

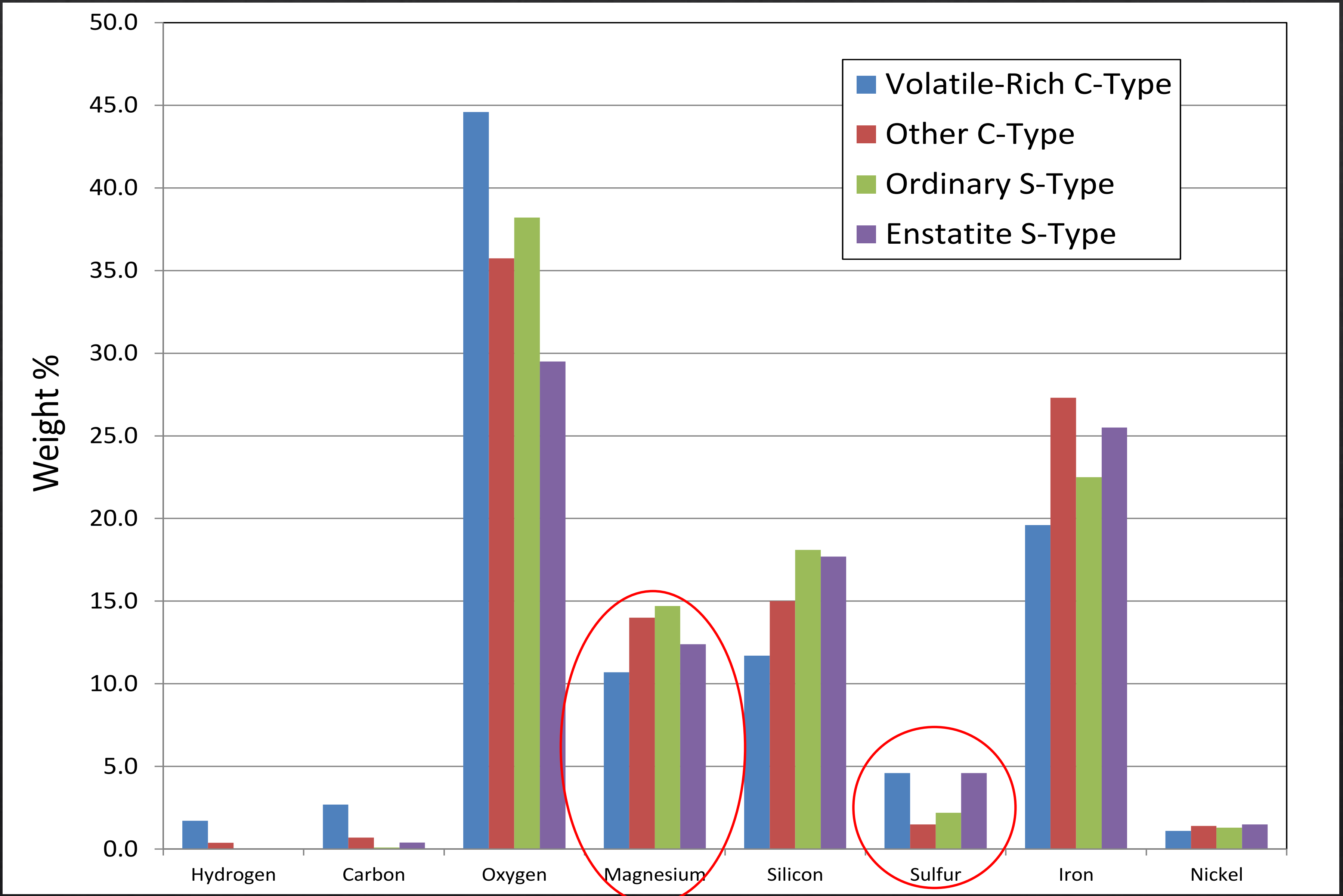
- Applied force is essentially independent of the asteroid characteristics
- Ions act as kinetic impactors
- Enables large stand-off distance from the asteroid
  - Requires small ion beam divergence angle
- Can engineer the applied force (power) and propellant usage (specific impulse)
- Must thrust in opposite directions simultaneously





Asteroid Mining

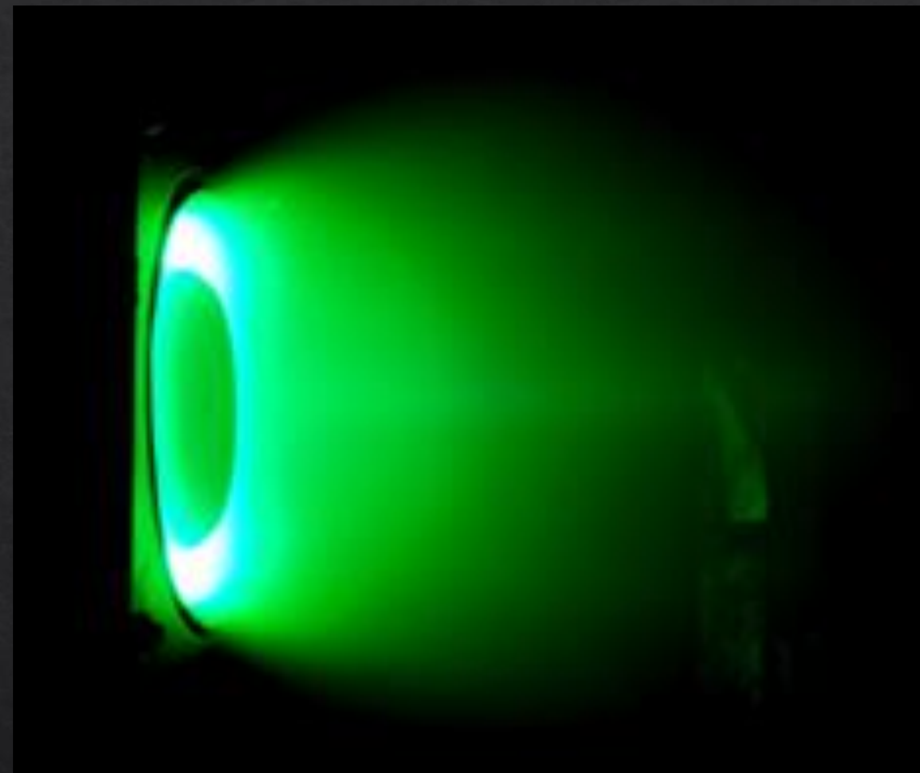
In Space Resource Utilization



Hutchison, R., "Meteorites, A Petrologic, Chemical and Isotopic Synthesis," *Cambridge University Press*, 2004, ISBN 0 521 47010 2.

Asteroid-Derived Hall Thruster Propellants

A magnesium-fueled Hall thruster from Michigan Technological University



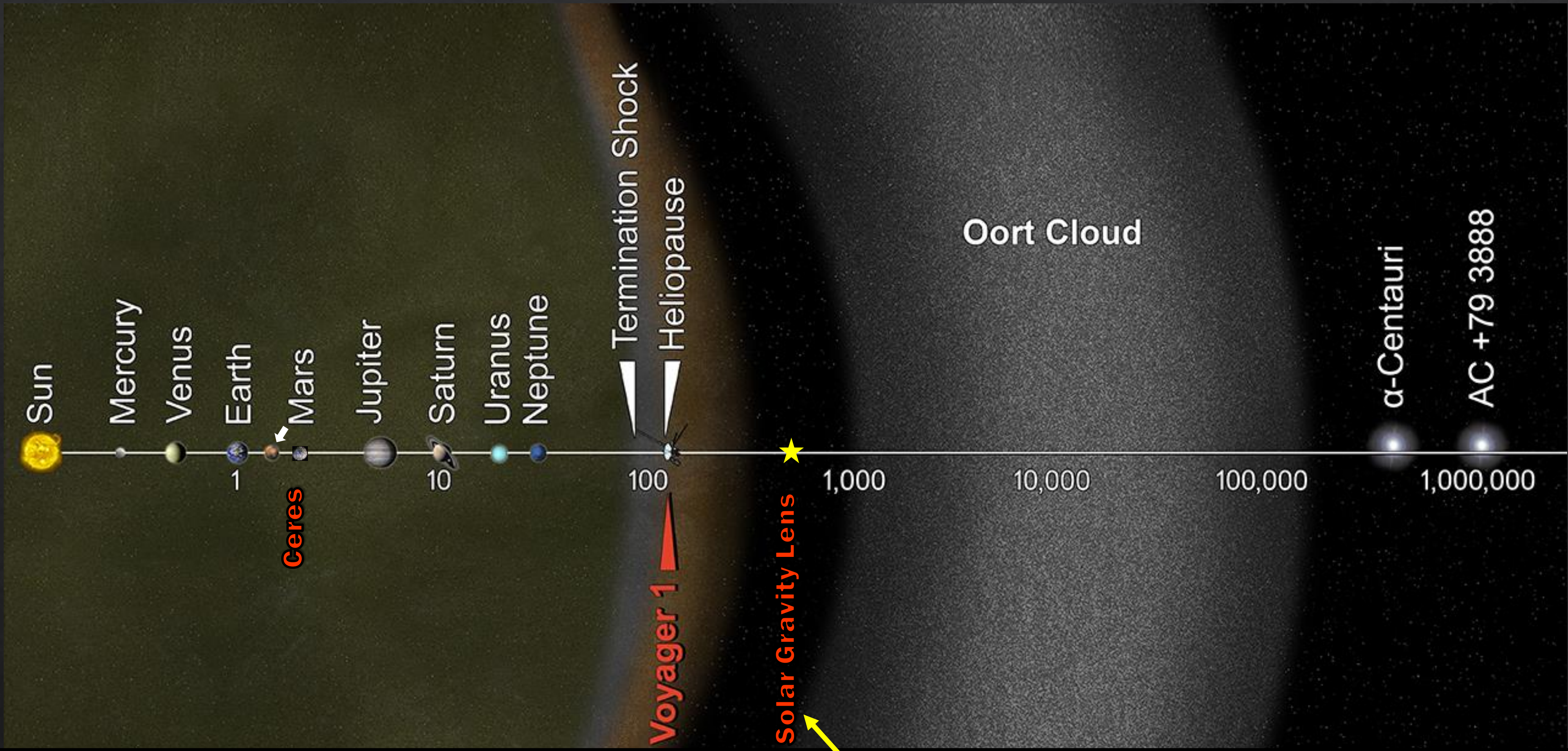
	Molecular Weight	Melting Point	Boiling Point	Ionization Energy (eV)			Vapor Pressure			
	(AMU)	(C)	(C)	1st	2nd	Temperature	1 Pa	10 Pa	100 Pa	1000 Pa
Magnesium	24.31	650	1091	7.65	15.04	T (K)	701	773	861	971
Sulfur	32.06	115	445	10.36	23.34	T (K)	375	408	449	508
Xenon	131.3	-112	-108	12.13	21.21	T (K)	83	92	103	117

Ultra-High ΔV Missions

Solar Gravity Lens Mission Concept

Want to go to > 550 AU in less than 15 years (~40 AU/year)

Space is BIG



> 40 AU/year

3.6 AU/year

How Fast Do We Want to Go?

Faster than a speeding bullet? 0.8 km/s

325X

- A speeding bullet would take > 3000 years to go to the solar gravity lens location

NASA's Dawn spacecraft has an ion propulsion system on board. It is the best on-board propulsion system ever flown in deep space.

- How fast did Dawn go? 11 km/s

NASA's Voyager 1 spacecraft used Jupiter and Saturn gravity assists to make it the fastest spacecraft ever flown

- How fast is Voyager 1? 17 km/s

If we want to go to the solar gravity lens location in [illegible] years.

- How fast do we have to go? 260 km/s

Three Key Features of Our Proposed Architecture to Go Fast

1

High Power

Don't carry the power source—laser beam power to the spacecraft

2

Small Dry Mass

Collect the laser power and convert it to electricity to power the ion drive system

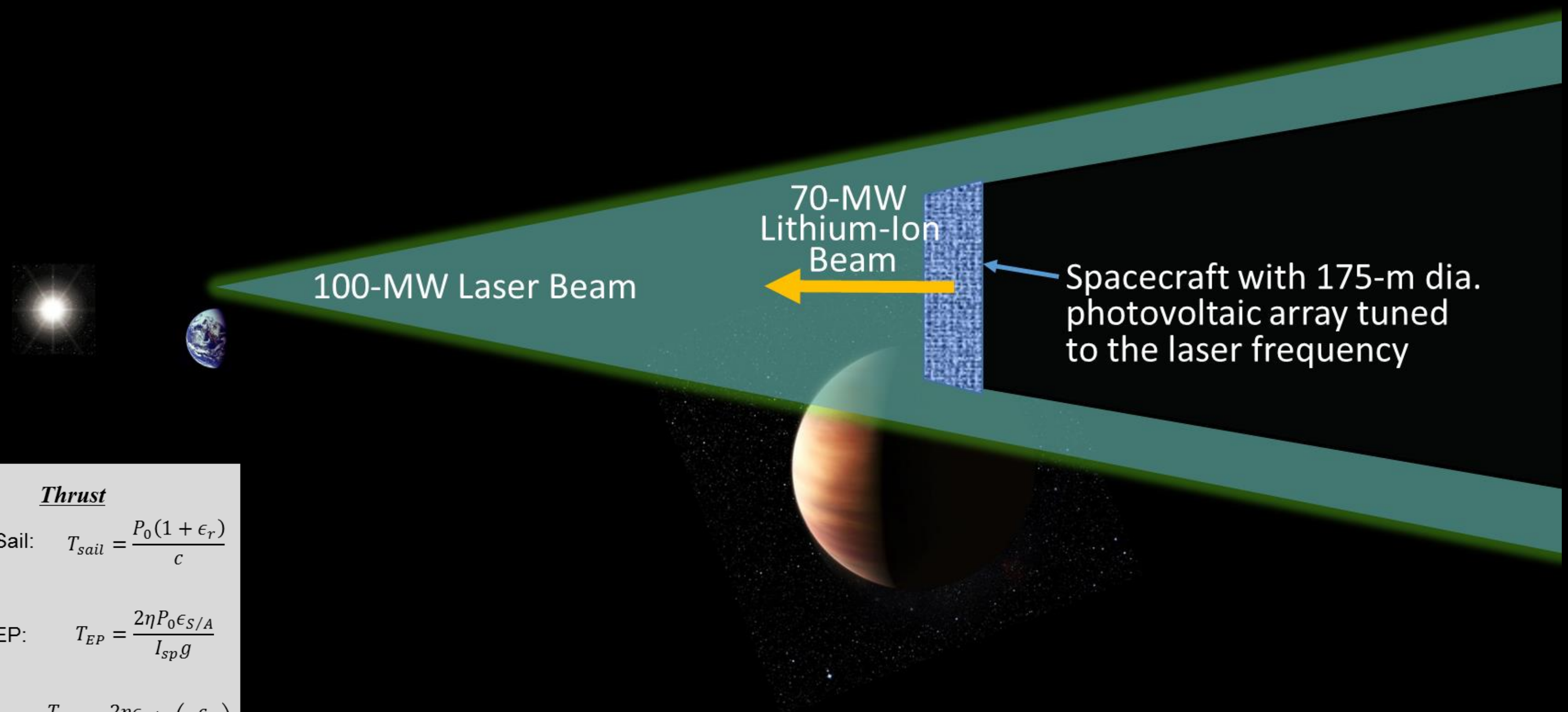
3

Small Propellant Mass

Increase the exhaust velocity, v_{ex} by a factor of 10 over the best ion engines today

Artist's concepts

Laser Electric Propulsion (LEP) Concept



Thrust

Laser Sail: $T_{sail} = \dfrac{P_0(1+\epsilon_r)}{c}$

Laser EP: $T_{EP} = \dfrac{2\eta P_0 \epsilon_{S/A}}{I_{sp} g}$

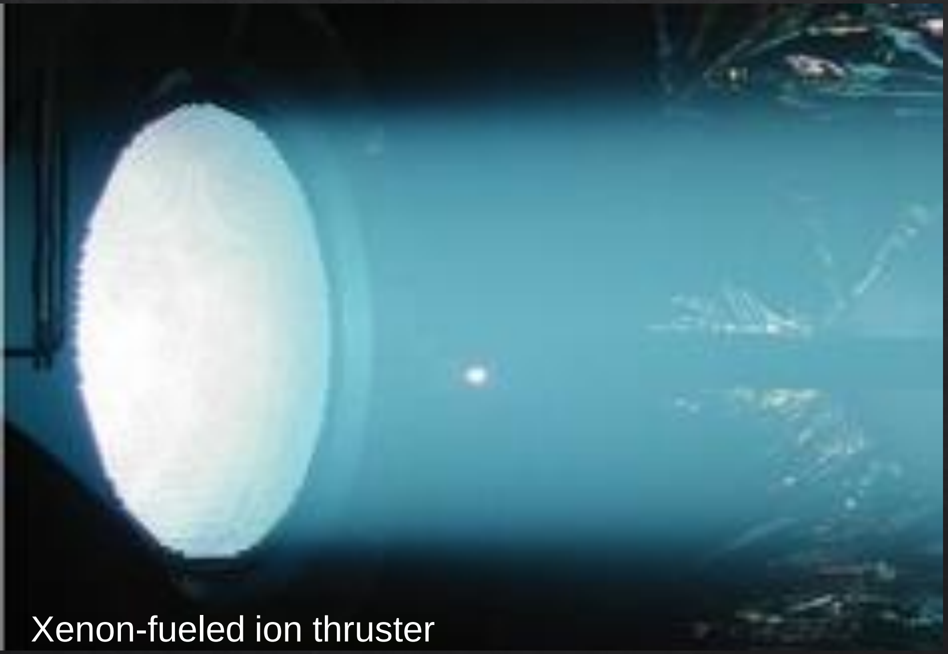
Ratio: $\dfrac{T_{EP}}{T_{sail}} = \dfrac{2\eta\epsilon_{S/A}}{1+\epsilon_r}\left(\dfrac{c}{I_{sp} g}\right)$

Space-based laser powers a 60,000-s Isp vehicle past Jupiter on a 12-year trip to 500 AU

Artist's concept

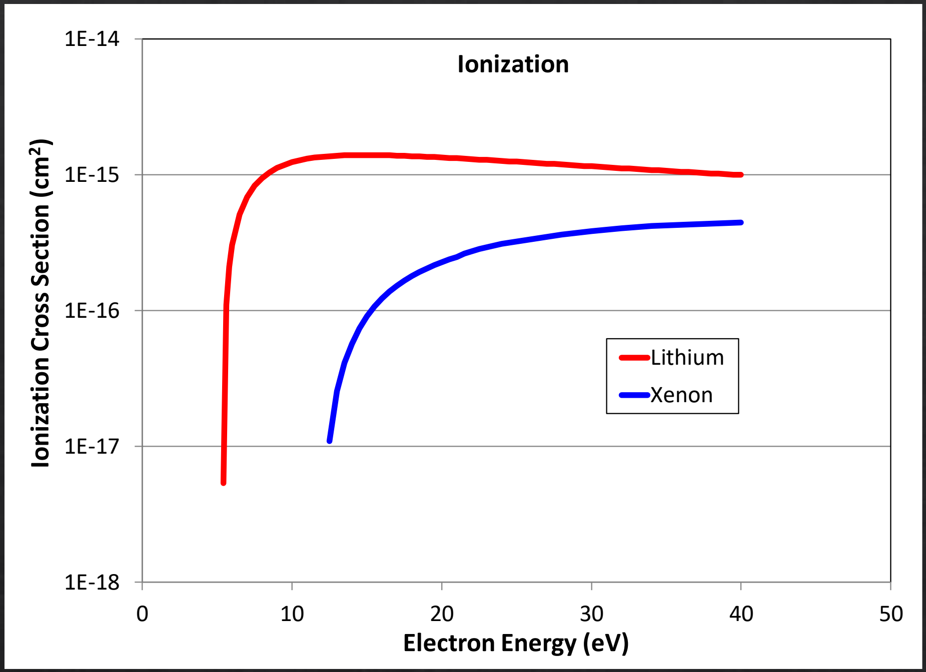
Lithium-fueled Ion Thruster

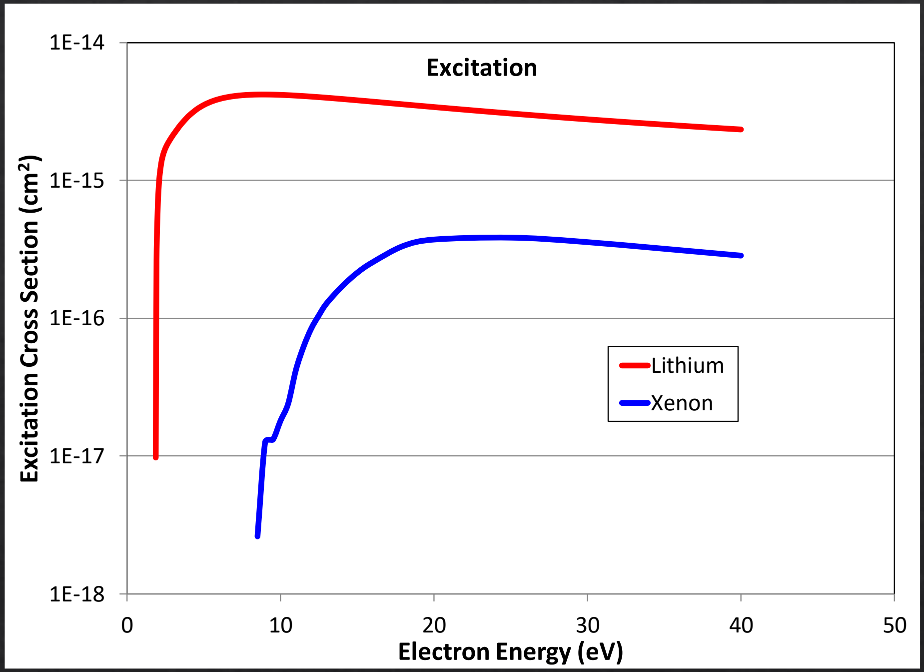
10X the exhaust velocity of the best ion engines today


Xenon-fueled ion thruster

Parameter	State of the Art	Lithium Thruster
Propellant	Xenon	Lithium
Exhaust Velocity	50 km/s	500 km/s
Input Power	16 kW	7,000 kW
Thrust	0.4 N	26 N
Efficiency	0.74	0.95

Xenon vs Lithium Plasmas

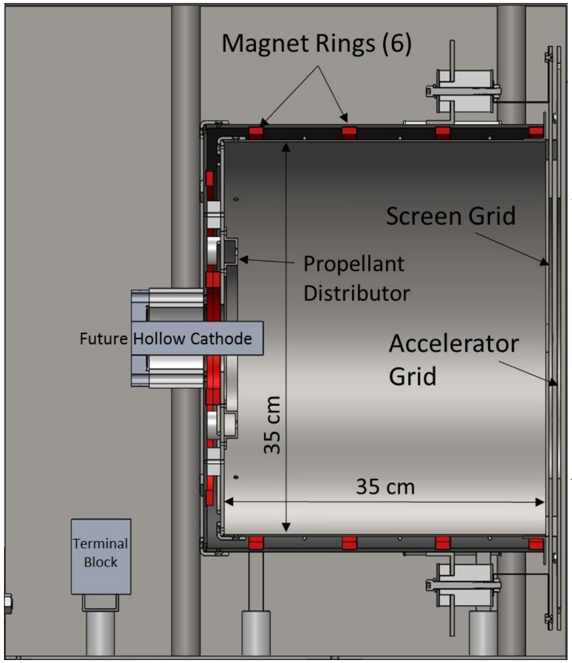




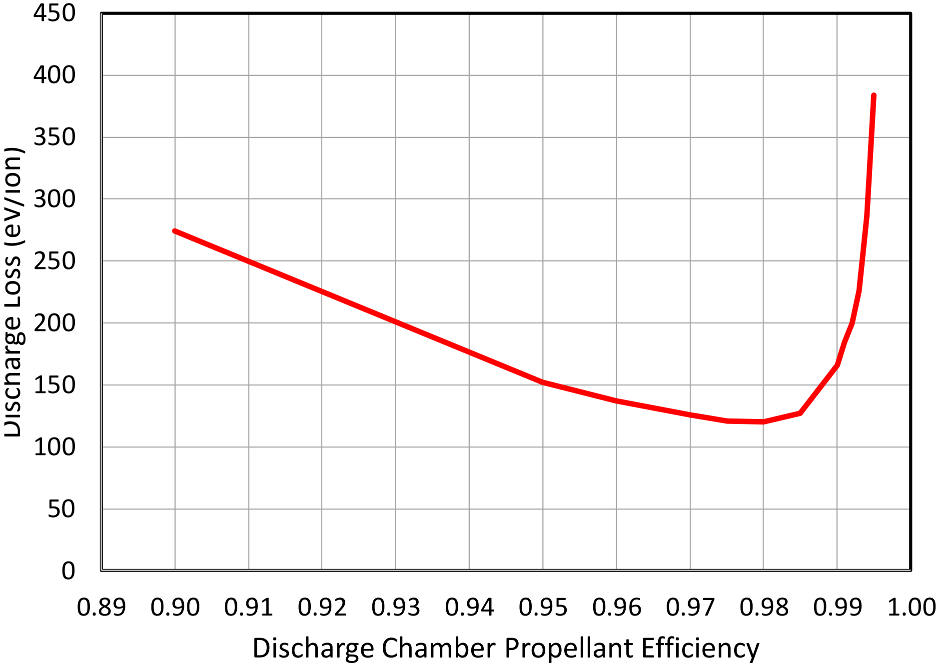
- Lithium is much easier to ionize than xenon
- Lithium also has a much larger excitation cross section than xenon
- The first ionization potential for lithium is 5.39 eV and the second ionization potential is 75.64 eV
  - For low voltage discharges, lithium will be nearly impossible to doubly ionize

Discharge Chamber

Configuration

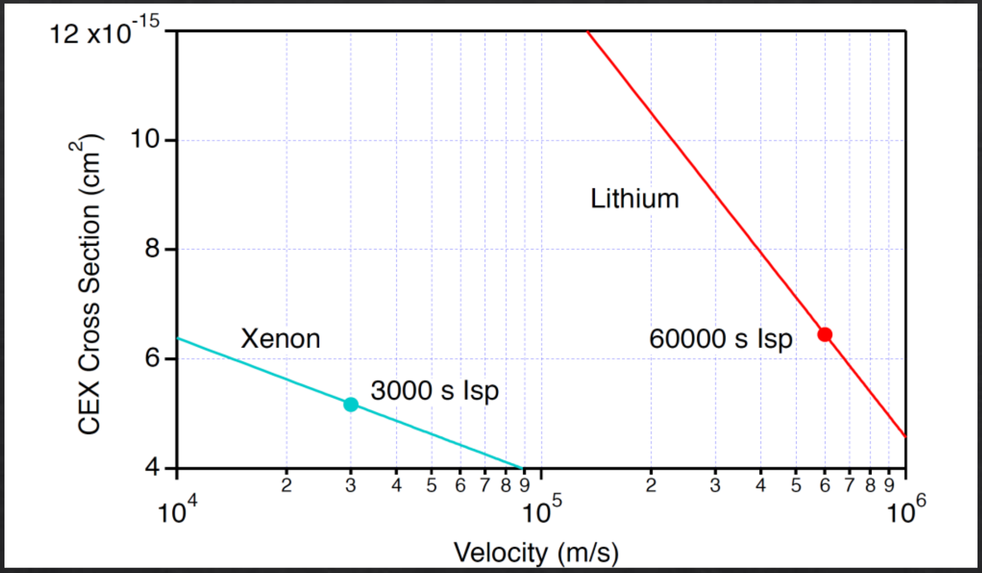


Discharge Performance Curve

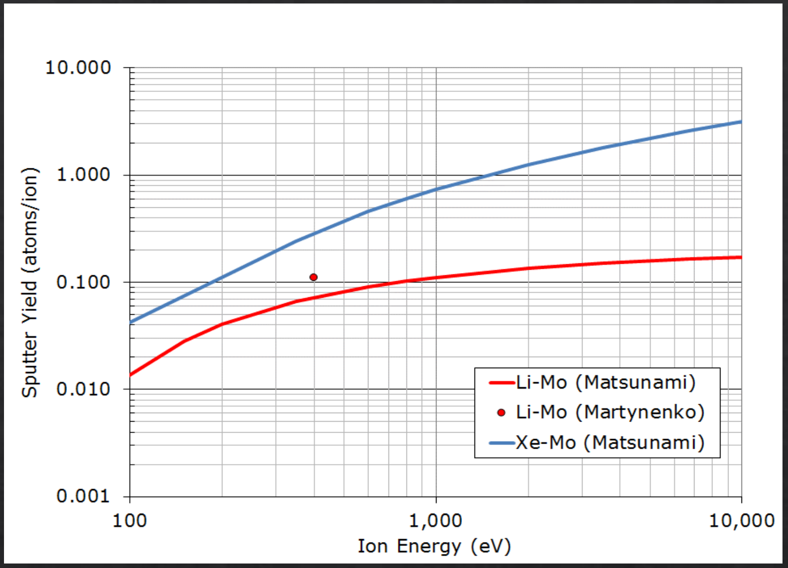


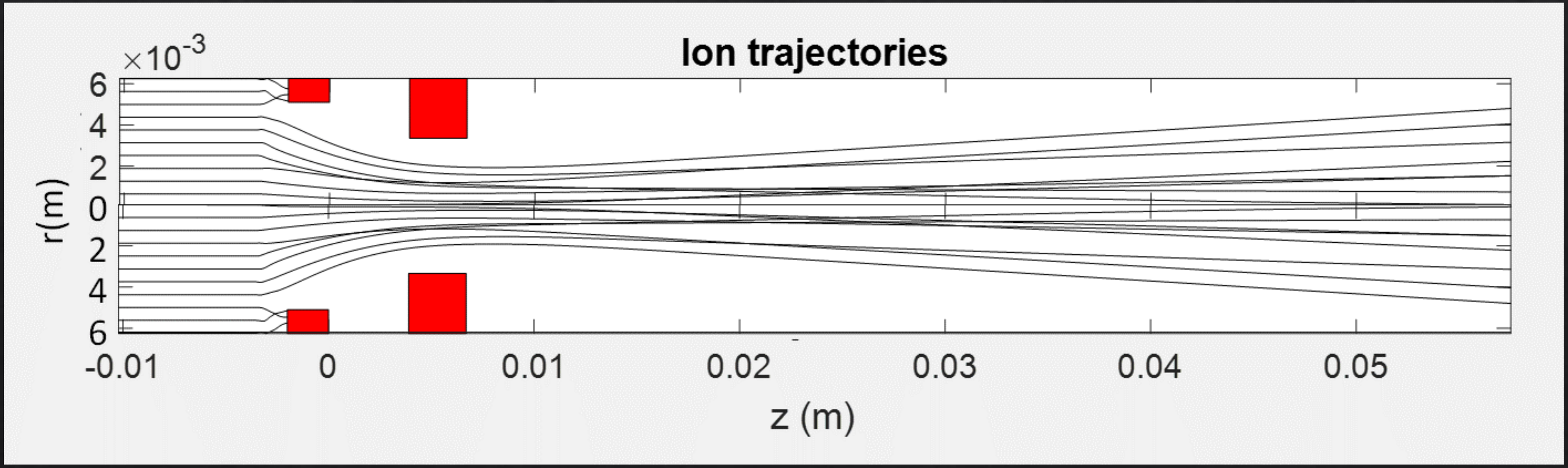
Ion Optics

Charge Exchange Collision Cross Sections

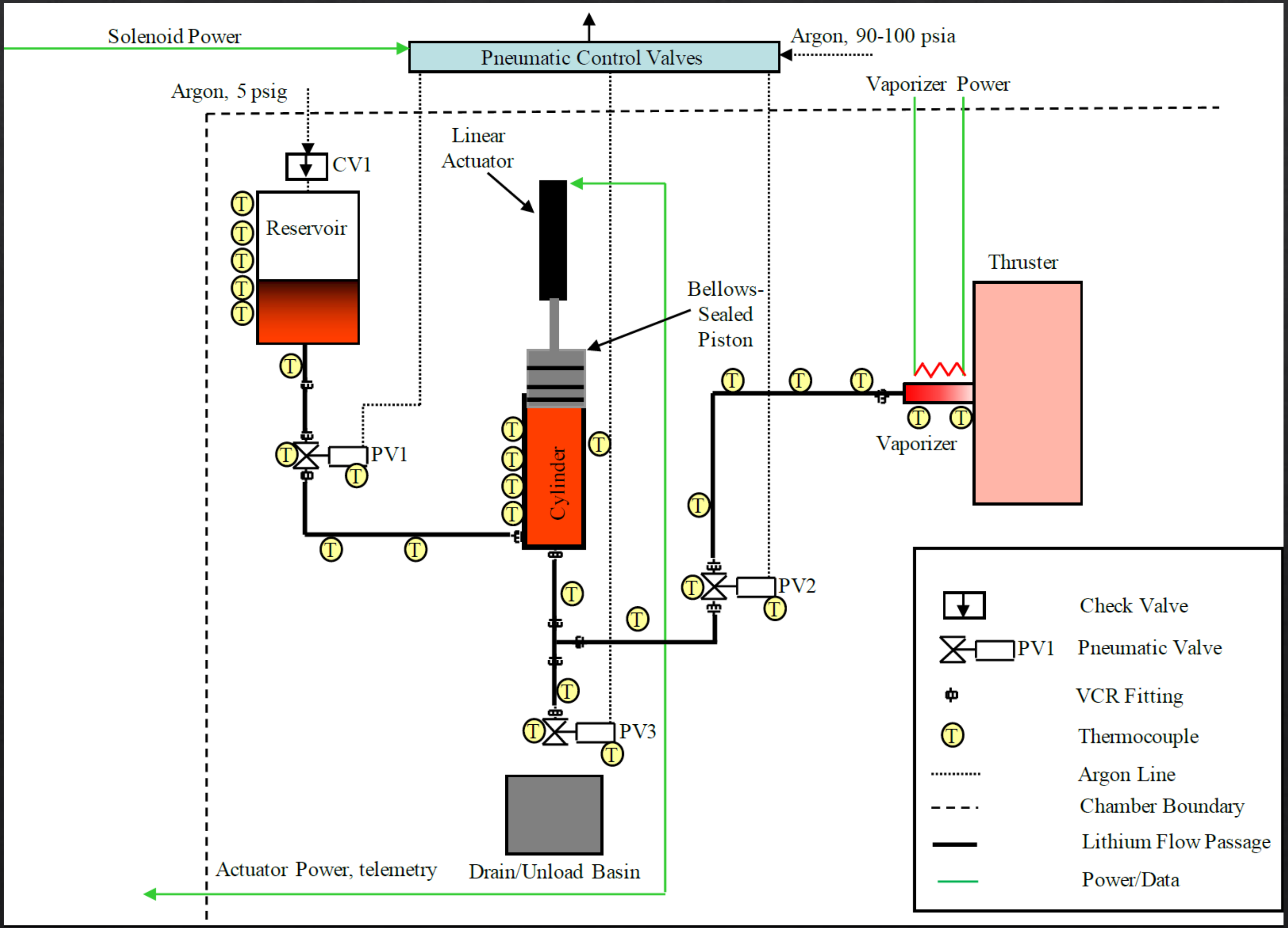


Sputter Yield





Lithium Feed System



Lithium-Test Facility

Lithium-Test Chamber

- 3 m diameter x 8 m long
- Conical Liner
  - 1.68 m to 2.44 m
  - 5.16 m long
  - 38 m^2 surface area
- Lithium Pumping Speed
  - 9,000,000 L/s

Why Lithium?

- *Lithium is way cool!*
- An ion thruster with a specific impulse of 50,000 s would enable deep space missions with characteristic velocities in the range 100 km/s to 200 km/s.
- Lithium enables specific impulses of tens of thousands of seconds at voltages less than 10 kV.
- Discharge chamber modeling suggests that it may be possible to operate the discharge chamber at a propellant efficiency of 99%.
  - Minimize charge-exchange erosion of the accelerator grid
  - Minimize CEX plasma interaction with a high-voltage PV array
- Lithium is much easier to store on a spacecraft than hydrogen or helium.

Summary

- The Rocket Equation drives the need for Electric Propulsion
  - Has resulted in 25 countries around the world developing this technology
- Electric Propulsion is in widespread use on Commercial Communication Satellites
- Electric Propulsion is expanding its footprint on deep space robotic science missions
- Electric Propulsion is currently the technology of choice for human missions to Mars
- Electric Propulsion is applicable to most Planetary Defense techniques (KI, nuclear deflection, gravity traction, laser ablation)
  - It’s largest contribution may be through ion beam deflection
- Electric Propulsion may play a dominant role in asteroid mining
- Electric Propulsion, in combination with power beaming, may enable fast transportation throughout the solar system up to approximately the solar gravity lens location